

# Monolithical Integration of Semiconductor Optical Amplifiers and Passive Mode-Filters for Low Facet Reflectivity

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*Low facet reflectivity in SOAs is essential for suppressing gain ripple. Low residual reflectivity can be realized by tilting the output waveguide with respect to the facet and by applying wide waveguides. Since wide waveguides result in higher-order mode reflections with significant reflection coefficients, these higher-order modes must be filtered out. We present numerical and experimental results on ridge waveguide SOAs which have been monolithically integrated with passive ridge waveguides with mode filters. As a result, we obtained a residual reflectivity lower than -30 dB without anti-reflection coating.*

## Introduction

Semiconductor Optical Amplifiers (SOAs) are key components in optical chips and in future WDM networks. Reflection at the facets of a SOA must be kept low, because it causes gain ripple due to Fabry-Perot resonances. A reflection coefficient below -40 dB over the 3 dB gain bandwidth of the SOA is required, which results in approximately 1 dB ripple for 28 dB on-chip gain. Low reflectivity can be achieved by applying an Anti-Reflection (AR) coating [1] in combination with a reflection-reducing waveguide geometry at the facets. In the literature, several methods for reducing the facet reflectivity in optical amplifiers by means of geometry have been reported, such as angled facets, which reflect the back reflections away from the SOA [2], buried facets (windows), which diverge the output beam and reduce the coupling of the reflected beam [3, 4], and combinations of these methods [5]. When using methods like buried facets, the location of the output facets is fixed, which imposes strict requirements on the cleaving accuracy. In contrast, simply cleaving through the waveguides offers maximal flexibility. However, in as-cleaved waveguides, the higher-order waveguide modes will experience high reflectivity [6, 7, 8]. In this paper we report on the integration of SOAs with passive mode-filters in order to suppress higher-order modes for a low residual reflectivity.

## Device Fabrication

All epitaxial layers for the SOA were grown by Low-Pressure Metal-organic Vapour Phase Epitaxy (LP-MOVPE) at 625 °C. The SOA active layer consists of a 120 nm thick InGaAsP ( $\lambda_{\text{gap}}=1550$  nm) layer embedded between two InGaAsP ( $\lambda_{\text{gap}}=1250$  nm) layers. The InGaAsP film layer was cladded by a 200 nm thick p-InP layer. Next, the active layer stack was butt-joint to an InGaAsP ( $\lambda_{\text{gap}}=1250$  nm) layer for the passive sections by the

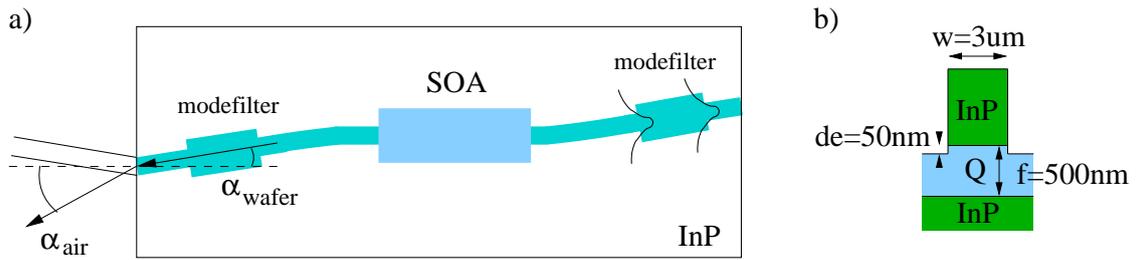


Figure 1: a) SOA with mode-filters and angled-facet outputs. b) Cross section of the waveguide structure at the facet.

procedure described in [9]. In the third epitaxy step a 1300 nm thick p-InP cladding layer and the p-InGaAs contacting layer were grown.

The waveguide mask layer was defined in 100-nm PECVD-SiN<sub>x</sub> using contact photolithography on positive photo resist. The SiN<sub>x</sub>-layer was etched using CHF<sub>3</sub> reactive ion etching. The ridge waveguides were etched employing an optimized CH<sub>4</sub>/H<sub>2</sub> etching process and an O<sub>2</sub> descumming process [10]. The amplifiers were passivated with a 380- $\mu$ m-thick SiN<sub>x</sub>-layer before metalization.

## Design

In SOAs, the reflectivity from the output facets must be low in order to keep the gain ripple below 1 dB. For this purpose, we have realized a SOA with integrated mode-filters and angled facets, as shown in figure 1. An easy way for reducing the facet reflectivity is tilting the output waveguide with respect to the facet of the chip. This reduces the coupling efficiency of the back reflected light into the SOA. At the left side of the figure, the virtual waveguide to which the reflected beam couples is shown. The effect of the waveguide angle on the reflectivity on the fundamental mode is shown in Figure 2. It can be seen that an increase in the angle will decreasing the modal reflection coefficients. Also, a wider waveguide allows for a smaller angle without compromising the reflectivity. This is very attractive because a small angle eases fiber-chip coupling. For example, a 3.0  $\mu$ m waveguide at a 7° reduces the facet reflectivity of the fundamental mode below -30 dB. On the other hand, a 1.0  $\mu$ m waveguide requires an angle that is more than twice as large. The peaks in the figure with a very low reflectivity are too narrow for practical use when considering the fabrication tolerances for deviations in waveguide width, film layer thickness and etch depth.

Facet reflections also involve higher-order modes, which have relatively high reflectivity at small angles. Figure 3 shows the reflection coefficients from the 0<sup>th</sup> and 1<sup>st</sup> order mode, and the reflective conversion from the 0<sup>th</sup> to the 1<sup>st</sup> order mode in a 3.0  $\mu$ m waveguide. The 1<sup>st</sup> order mode reflections are seen to drop below -30 dB only for angles beyond 11°, which results in large 35° angles in air. Reflections involving higher-order modes can be suppressed conveniently by inserting MMI mode-filters [11] between the facets. Figure 4 shows the simulated transmission of the filter with a size of is 6  $\mu$ m by 98  $\mu$ m. The filters show negligible transmission loss (< 0.05 dB) in the fundamental order mode, which has been experimentally verified using Fabry Perót loss measurements. The first-order mode is suppressed by almost -10 dB. Note that for each facet reflection, the light passes the

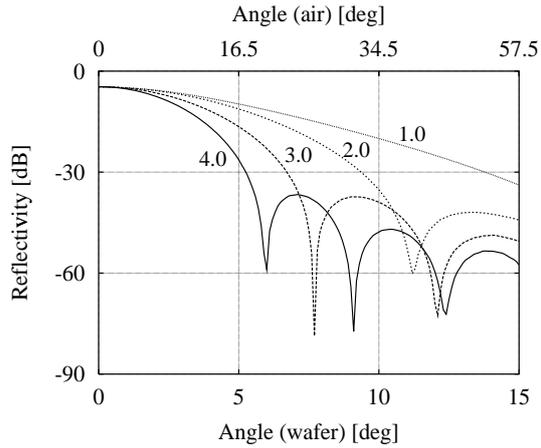


Figure 2: Reflectivity of the fundamental mode for waveguide widths varying from 1.0  $\mu\text{m}$  to 4.0  $\mu\text{m}$ .

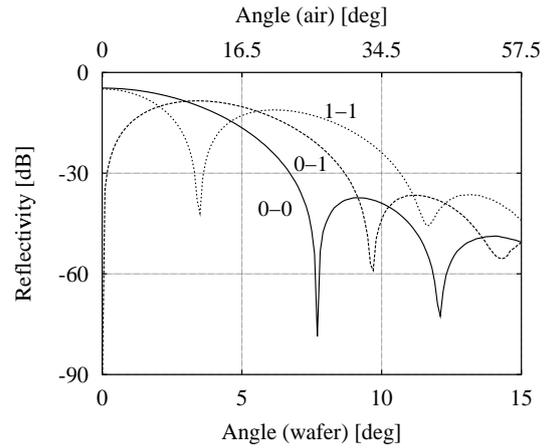


Figure 3: Angled facet reflectivity between waveguide modes in a 3- $\mu\text{m}$ -wide waveguide. Shown are the reflectivity between the 0<sup>th</sup> and 1<sup>st</sup> order modes.

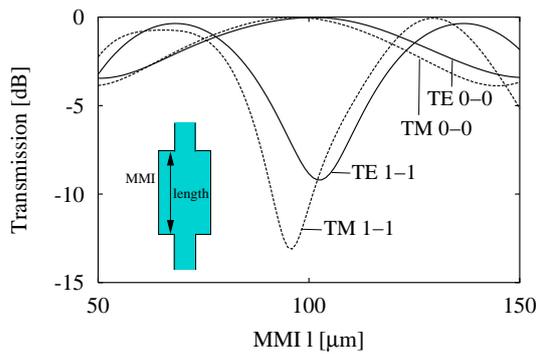


Figure 4: Modelfilter transmission for TE and TM from mode 0 to 0 and from mode 1 to 1.

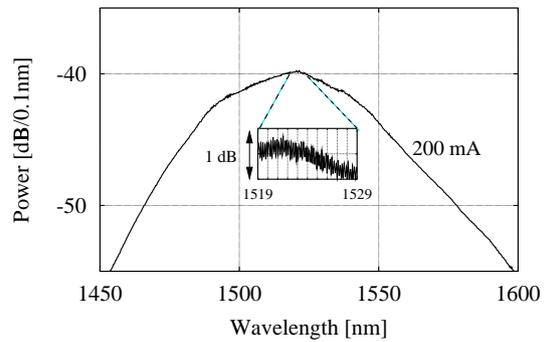


Figure 5: ASE spectrum of a 600- $\mu\text{m}$ -long SOA in a 4300- $\mu\text{m}$ -long cavity with passive mode-filters.

mode-filter twice. A tolerance analysis showed that the mode-filter has stable operation over a 100 nm wavelength span and is robust against fabrication errors.

## Measurement results

The Amplified Spontaneous Emission (ASE) spectrum of a SOA with 7° angled facets and mode-filters on both sides is shown in figure 5. The SOA is biased at 200 mA and the peak gain wavelength is at 1520 nm. The peak gain at this bias was estimated to be at least 20 dB, while the bandwidth of the amplifier is over 50 nm. Gain ripple at the peak gain wavelength, shown in the inset of figure 5, is less than 0.5 dB. The reflectivity  $R$  was found to be smaller than  $-30$  dB by using the relation  $R = G(\sqrt{P_{\text{out}}^+} - \sqrt{P_{\text{out}}^-}) / (\sqrt{P_{\text{out}}^+} + \sqrt{P_{\text{out}}^-})$ . Here  $P_{\text{out}}^+$  is the maximum power in the ripple,  $P_{\text{out}}^-$  is the minimum power and  $G$  is the gain.

## Conclusions

We have realized the integration of SOAs with passive mode-filters for low facet reflectivity without applying an AR coating. The 3- $\mu\text{m}$ -wide output waveguides enable low reflectivity below -30 dB in the fundamental mode at 7° angled facets. The gain ripple in a device containing a SOA and two mode-filters was shown to be around 0.5 dB at an estimated 20 dB gain. Therefore, the reflectivity in the higher-order modes was suppressed effectively.

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